IL NUOVO CIMENTO **41 C** (2018) 218
DOI 10.1393/ncc/i2018-18218-1

Colloquia: SIRR 2018

The equilibrium factor in the radon dose calculation in the archaeological site of *Acquedotto Augusteo del Serino* in Naples

G. La Verde(1)(2), V. Roca(1)(2), C. Sabbarese(2)(3), F. Ambrosino(3) and M. Pugliese(1)(2)(*)

(1) *Department of Physics "E. Pancini", University of Naples Federico II - Naples, Italy*
(2) *National Institute of Nuclear Physics, Section of Naples - Naples, Italy*
(3) *Department of Mathematics and Physics, University of Campania "L. Vanvitelli" Caserta, Italy*

received 4 December 2018

Summary. — The calculation of the dose from exposure to radon gas is regulated by the Italian Legislative Decree 241/2000. It takes into account the activity concentration of the radon gas, the exposure time and the conversion factor (equal to 3 nSv/Bq·m^3·h) which includes the value of the equilibrium factor (F), set to be 0.4. Since high concentrations of radon are found in particular in some underground environments, it is important to evaluate the real exposure dose of workers, by estimating the value of F on a case-by-case basis exposure dose of workers. Measurements have been made with the E-RPISU system, which allows the simultaneous assessment of the concentration of radon gas activity in air and of its progeny. In this preliminary investigation, measurements were carried out in locals of the ancient site of the *Acquedotto Augusteo del Serino* in the Sanità district in the historic center of Naples, and the results confirmed the importance of calculating the value of the equilibrium factor in order to obtain a correct and realistic estimate of the exposure dose.

1. – Introduction

The calculation of the dose from exposure to radon gas is covered by the Legislative Decree 241/00. It takes into account the concentration of activity of the radon gas, the exposure time and the conversion factor (equal to $3\,\text{nSv/Bq} \cdot \text{m}^3 \cdot \text{h}$) which includes the value of the equilibrium factor (F), whose average value is been established to be 0.4 [1]. The importance of the concentrations of radon gas decay products in the atmosphere

(*) Corresponding author. E-mail: pugliese@na.infn.it

and, consequently, the equilibrium factor, is due to the key role they play in dosimetry. In the model proposed by ICRP [2] it is in fact well known that the internal inhalation and deposition dose in the human respiratory system due to radon and its products is described by the following formula:

$$E = C_{\mathrm{Rn}} \cdot t_{\mathrm{exp}} \cdot F \cdot DCF, \tag{1}$$

where E is the effective dose (mSv), C_{Rn} is the concentration of radon activity (Bq/m^3), t_{exp} is the exposure time in hours, DCF a conversion factor (dose conversion factor), F the equilibrium factor.

The estimate of the effective dose is influenced, as well as by F, by the variability of DCF, due to the concentration and the nature of the suspended particulate and it is dependent on the breathing modes. The ICRP proposes an average value for DCF of $12\,\mathrm{nSv/Bq \cdot h \cdot m^3}$. On the other hand, the Italian legislation (Legislative Decree 241/00) applies the following formula:

$$E = C_{\mathrm{Rn}} \cdot t_{\mathrm{exp}} \cdot f, \tag{2}$$

where f is a conversion factor of $3 \cdot 10^{-9}\,\mathrm{Sv/Bq \cdot m^3 \cdot h}$, and includes F.

However, it is not always representative of the real situations that can arise, since F can vary in a range comprised between 0.1 and 0.9.

In a closed system the secular equilibrium between radon and its short-lived decay products is reached in just over three hours and generates equal concentrations of activity among all of them. In the assessment of the biological damage caused by radon and its descendants, only the contribution deriving from the alpha decay is considered [3].

Actually, it turns out that a closed system does not exist, radon decay products are subject to the plate-out phenomenon. Most of the radon decay products are deposited on indoor surfaces, which deposition makes the radon decay products not available for inhalation [4].

For a given radon concentration, it has been reported that the extent of the particle deposition on surfaces depends strongly on the surface-to-volume ratio, on the electrostatic charge on persons, on the electrostatic charge on objects and on air movements [5].

For these reasons, the secular equilibrium is hardly attainable and the equilibrium factor represents that quantity which describes the deviations from the secular equilibrium and is defined by the following formula:

$$F = \frac{EEC\ (^{222}\mathrm{Rn})}{C_{\mathrm{Rn}}} = \frac{0,150 \cdot [^{218}\mathrm{Po}] + 0,516 \cdot [^{214}\mathrm{Pb}] + 0,380 \cdot [^{214}\mathrm{Bi}]}{C_{\mathrm{Rn}}}, \tag{3}$$

where C_{Rn} represents the real radon concentration and EEC (equilibrium equivalent concentration) is the equilibrium radon concentration with its decay products, which produces a value of $PAEC$ (potential alpha energy concentration) equivalent to the radionuclide mixture actually present. The EEC value is calculated by weighting the concentrations of the daughters with appropriate coefficients equal to the ratio between the energy of the alpha particle emitted by each radionuclide and its decay constant.

The location in which the measurements were carried out are the rooms located on the basement of the Peschici-Maresca palace, in Naples that are subjected to measures of concentration of the radon gas activity pursuant to the Legislative Decree 241/00.

2. – Material and methods

To experimentally measure the equilibrium factor and, therefore, for the simultaneous evaluation of the average concentration of radon gas activity in air and the average concentration of radon decay products, the E-RPISU system (Environmental radon Progeny Integrating Sampling Unit) was used [6].

The E-RPISU is basically composed of an air sampling pump, a flow meter, two specially modified short-term electret ion chambers, called RPISU chambers, with an appropriate filter holder, two normal short-term electret ion chambers and four electrets. The standard electrets and the readers used in the E-PERM System are usable with this unit.

An air-sampling pump is used to collect the radon progeny for a known sampling time on a $3.5\,\text{cm}^2$ glass fiber filter sampler mounted on the side of an RPISU chamber.

The alpha radiation emitted by the progeny collected on the filter ionizes air in the electret ion chamber. The ions are continuously collected by the electret, providing integrated alpha activity collected on the filter paper.

The flow rate can be adjusted for a desired value. The recommended flow rate is 0.5 liter per minute and the sampling duration chosen is 48 hours [7].

Knowing the radon gas activity and the activity of its decay products it is possible to derive the real value of the equilibrium factor.

In this preliminary investigation, measurements have been taken in a particular underground environment. In 2011, in the underground rooms of *Palazzo Peschici-Maresca* in Naples, two sections of the ancient *Acquedotto Augusteo del Serino*, composed of an interesting succession of pillars and arches in bricks and Neapolitan yellow tuff, were discovered and identified. This aqueduct for position, complexity and constructive peculiarities is one of the most impressive infrastructures of the Roman period in the ancient world and so it represents an archaeological testimony of exceptional interest, becoming the object of guided tours.

The tourist guides who work on the site must be protected from exposure to radon gas as this is an underground place dug into the tuff, where radon can reach concentration levels which are even very high. For this reason, the workers must be subject to surveillance, as required by the Legislative Decree 241/00.

Currently the employer states that the hours of work of the guides are about 3 hours a day for 3 days a week, for a total of 450 hours a year, very few to compromise human health. But the archaeological site is growing, the visits increase and soon the working hours of the guides could increase. This is why it is important to know the risk associated with radon gas from now on.

3. – Results and discussion

The E-RPISU was installed in the central hall of the site (as shown in fig. 1) and a 48 h measurement was performed during the normal activity of tourist guides.

The results are reported in table I.

The results of measurements are listed in table II.

Fig. 1. – Scheme of measurement archaeological site and E-RPISU position.

EEDC represents the equilibrium-equivalent decay-product activity concentration and it is given by

$$EECD = \frac{I - F + Q}{D \cdot C \cdot L}, \tag{4}$$

where I = RPISU room initial voltage reading, F = final voltage reading of the RPISU camera, Q = correction factor for the exposure queue, D = duration of exposure in days, L = flow in liters per minute.

TABLE I. – *Spreadsheet and acquisition of data from the E-RPISU system, where I and F are the initial and final voltage of the RPISU detector (volt), G and H the initial and final voltage of the radon detector (volt), D the duration of the measurement (days), FRL-PM the flow (liters per minute). Range: range fund rate (nGy/h).*

I	***F***	***G***	***H***	***D***	**FR-LPM**	**Gamma**	
638	580	691	527	2	0.5	390	
E-RPISU Template-LT electret							
I	***F***	CF	**FR-LPM**	**Days**	Q	RP-WL	
638	580	0.705626	0.5	2	0.87	0.083429	
E-RPISU Template-ST electret (BG due to radon and gamma)							
G	***H***	CF	FR	Days	Q	RP-WL	
691	527	8.820325	0.5	2	2.46	0.018872	
Net WL						**0.064557**	**5.01**
Radon template-ST electret							
G	***H***	CF	**Gamma**	Days	Radon pCi/L		
691	527	2.0474478	45	2	**36.15**		
Eqm ratio in percentage						**17.86**	

TABLE II. – *EEDC equilibrium-equivalent decay-product activity concentration.*

Results		
	Activity	Uncertainty (%)
EEDC (Bq/m^3)	241	5
Radon activity concentration (Bq/m^3)	1338	5
Equilibrium factor	0.18	

Q is given by

$$Q = \frac{(I - F) \cdot 0,03}{D}. \tag{5}$$

C is a calibration factor given by

$$C = \left(A + B \cdot \frac{I + F}{2} \right). \tag{6}$$

A and B are coefficients that depend on configuration.

The *radon gas concentration* (Bq/m^3) is given by conversion of radon concentration of radon template-ST electret from pCi/L to Bq/m^3

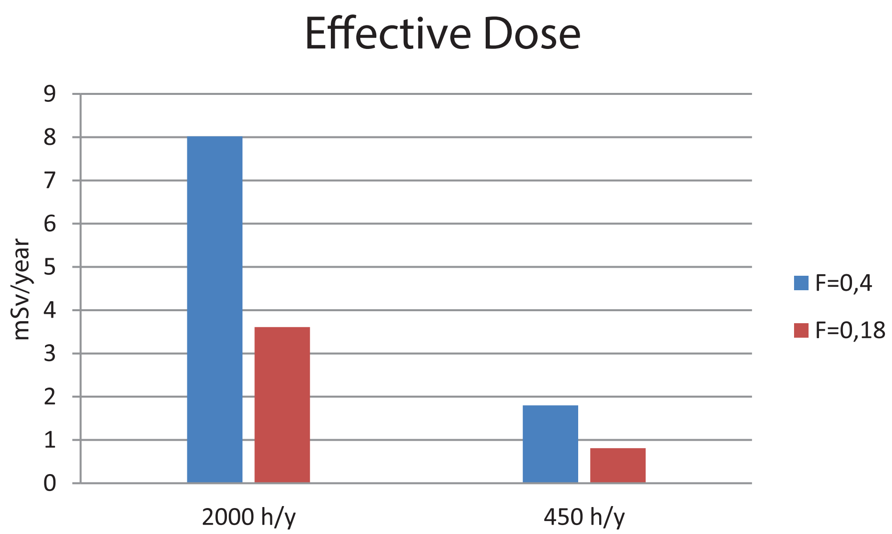

Fig. 2. – Calculation of the effective dose considering the fixed value of $F = 0.4$ and the experimentally measured value, in relation to the actual working hours and the theoretical working hours of a full-time job.

The *equilibrium factor* (F) is given by the ratio

$$F = \frac{EEDC}{\text{radon concentration}} = \frac{241\ (\text{Bq/mc})}{1338\ (\text{Bq/mc})} = 0.18. \qquad (7)$$

The value of F obtained with the experimental measurement is different from the average fixed value (0.4) used by the Legislative Decree 241/00, so that we proceeded with the calculation of the effective dose:

- using formula (1):

$$E = 1338\,\text{Bq/m}^3 \cdot 450\,\text{h} \cdot 0.18 \cdot 12\,\text{nSv/Bq/m}^3\text{h} = 0.81\,\text{mSv/y};$$

- using formula (2) of the Legislative Decree 241/00:

$$E = 1338\,\text{Bq/m}^3 \cdot 450\,\text{h} \cdot 3 \cdot 10^{-9}\,\text{nSv/Bq/m}^3\text{h} = 1.80\,\text{mSv/y}.$$

Substituting the value of the annual hours equal to 450 with 2000 (which corresponds to 8 hours a day for 5 days for a year) the effective dose is

- using (1) $E = 8.02\,\text{mSv/y}$;
- using (2) $E = 3.61\,\text{mSv/y}$.

4. – Conclusions

The value of $F = 0.18$ resulted in a significant lowering of the exposure dose value: from 1.80 mSv, calculated with the formula adopted by the current Legislative Decree 241/00 (1) which sets an average value for $F = 0.4$, to 0.81 mSv calculated with the formula (2) that takes into account the variability of F (fig. 2).

The limit value of the effective dose is 3 mSv/year.

In addition, a dose calculation was performed based on the exposure time, reporting 2000 h (average annual value considering 8 h/day for 5 days/week for one year) with 450 h (current tour guide exposure time). Also in this case, in anticipation of an increasing work rate up to cover 2000 h/year, the influence of the value of F was significant.

REFERENCES

[1] Decreto Legislativo n. 241/2000.
[2] ICRP, *Lung cancer risk from radon and progeny and statement on radon*, ICRP publication 115, *Ann. ICRP*, **40** (2010) 1.
[3] Swedjemark G. A., *Health Phys.*, **45** (1983) 453.
[4] Espinosa G. and Tommasino L., *J. Environ. Radioact.*, **143** (2015) 80.
[5] Miles J. C. H. and Strong J. C., *Radiol. Protection Bull.*, **21** (1989) 6.
[6] Kotrappa P., Stieff L. and Dempsey J., *An Advanced EPERM System For Simultaneous Measurement Of Concentrations Of Radon Gas, Radon Progeny, Equilibrium Ratio And Unattached Radon Progeny, Proceedings of the 2003 International Radon Symposium, October 5–8, 2003*, Vol. **II** (American Association of Radon Scientists and Technologists, Inc.) 2003.
[7] Kotrappa P., Stieff L. and Dempsey J., *Radon progeny monitor*, Patent number: 7312439.